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SEISMIC DATA LABORATORY QUARTERLY TECHNICAL SUMMARY REPORT

(JANUARY – MARCH 1967)

7 AUGUST 1967

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER

Washington, D. C.

By

TELEDYNE, INC.

Under

Project VELA UNIFORM

Sponsored By

ADVANCED RESEARCH PROJECTS AGENCY

Nuclear Test Detection Office

ARPA Order No. 624

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AVAILABILITY

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I. INTRODUCTION

This quarterly technical summary report covers the work performed during the period January through March 1967. Part of the work reported herein was performed under Contract AF33(657)-15919, which covered SDL operations for January and February 1967. Work previously completed or currently in progress is mentioned only as it relates to analyses completed during this reporting period.

Analyses completed, for which results have been reported, are discussed in Section II under descriptive headings. Section III contains a discussion of the support and service tasks performed for in-house projects and for other VELA-UNIFORM participants. Appendix A is a listing for those organizations receiving SDL data services during this period.

II. WORK COMPLETED

A. Detection of Surface Waves From Small Events at Teleseismic Distances

One of the important measures of source mechanism is the excitation of surface waves. This encompasses such estimates as total energy, radiation pattern, frequency spectrum, and radiation of Love wave energy relative to Rayleigh wave energy. At one time or another practically all of these estimates have been applied in the study of large magnitude events. However, because the surface waves from small events ($M \leq 5$) usually arrive at teleseismic distances with amplitudes at or below the noise level, special techniques must be employed to extract the desired information. The purpose of this analysis was to use a matched filter approach for detecting small amplitude surface waves, estimating their total energy content and determining their radiation pattern.

Basically the matched filter approach amounts simply to searching a record $x(t)$ for a known wave form $y(t)$. In particular, a least-squares approach was used and the following decision criteria were chosen to determine whether or not a signal was present:

1. A relative maximum in the envelope of $C(\tau)$ must fall in the expected time window based on travel-time information.

2. This value of $C_{max}(\tau)$ must be greater than or at least comparable to typical peak values in the envelope of $C(\tau)$ outside the expected time window.

3. An arrival must be detected within the proper expected time window at each of several stations.

The matched filter approach requires that one knows the desired or expected waveform in order to search effectively for that waveform in a noisy record. In order to obtain a suitable "expected" waveform and at the same time assure that propagation effects would be properly accounted for, we chose the surface wave from a larger event in the source region of interest as the filter $y(t)$. Thus, no matter how complicated the paths of propagation were, the paths for other events in the same source region would be nearly coincident with those of the larger event which produced $y(t)$, so the only major differences in recorded waveform would be source differences.

In order to test the effectiveness and sensitivity of the matched filter approach for surface waves, several test cases were investigated, being adding a known signal to actual noise at different signal-to-noise (S/N) ratios, effects of varying epicentral distance, and the effects of amplitude spectra on matched filter response.

The matched filter approach was then applied to actual data. Results for three different source regions - Aleutians (Amchitka), Kamchatka, and Hawaii - are given below. The observation stations are LRSM stations or VELA observatories in North America. The epicenter information for the three sets of events are given in Table I.

The organization in the figures to follow conforms to the standard format adopted for displaying all matched filter results for actual events. That is, a station set consists of four traces; the top trace is the signal $y(t)$, the second trace is the observed seismogram $x(t)$, the third trace is $C_{xy}(\tau)$, and the bottom trace is $C(\tau)$. The legend at the left gives values of distance, $\hat{a}$, and CC as well as station and event identification. The arrows indicate the location of the expected signal arrival at each station. This is where the peak in the matched filter output should occur; that is, the beginning point of $y(t)$ in $x(t)$. The interval between each time mark is 50 seconds unless otherwise indicated.

1. Aleutian Source Region

The LONGSHOT seismograms were scanned for surface waves with the earthquake signal used as the matched filter. Results showed that the Rayleigh waves were clearly detected at all but one station. Figure 1 is an example of these results. The Rayleigh wave amplitude of LONGSHOT relative to that of the magnitude 5.9 earthquake, however, was below .12 everywhere in the distance range analyzed (3500-7000 km). This means that the surface wave magnitude for LONGSHOT was only about 5.0 if the surface wave magnitude of the reference earthquake was equivalent to its body wave magnitude. It also means that the R/P excitation for the explosion was nearly an order of magnitude smaller than

Date	Area	Origin Time	Latitude	Longitude	Magnitude	Depth
25 Mar 66	Andreanof Is.	12:54:55.7	51.5 N	179.6 E	4.9	33
20 Feb 66	Rat Is.	8:27:58.0	51.5 N	179.5 E	4.0	48
22 Nov 65	Andreanof Is.	20:25:30.4	51.3 N	179.8 W	5.9*	40
29 Oct 65	Amchitka Is.	21:00:00.1	51.4 N	179.2 E	5.97	0(Longshot)
6 Jul 65	Kamchatka	4:58:55.7	55.1 N	162.1 E	5.1	33
20 Apr 65	Kamchatka	6:50:17.6	54.6 N	161.4 E	5.3	33
14 Feb 65	Komandorsky	17:01:13.9	55.1 N	165.6 E	5.0	20
29 Jan 65	Kamchatka	9:35:25.7	54.8 N	161.7 E	5.8*	33
21 Jan 65	Kamchatka	16:36:46.2	56.2 N	163.1 E	4.4	119
11 Oct 64	Hawaii	10:06:44.9	19.1 N	156.6 W	5.3*	33
13 Aug 64	Hawaii	16:27:35.4	19.5 N	155.4 W	4.1	11
7 Jan 64	Hawaii	11:06:21.0	18.6 N	155.9 W	4.4	33

*Used as filter for others in group

Table I - USCGS Study Epicenter Information
Used for Matched Filter

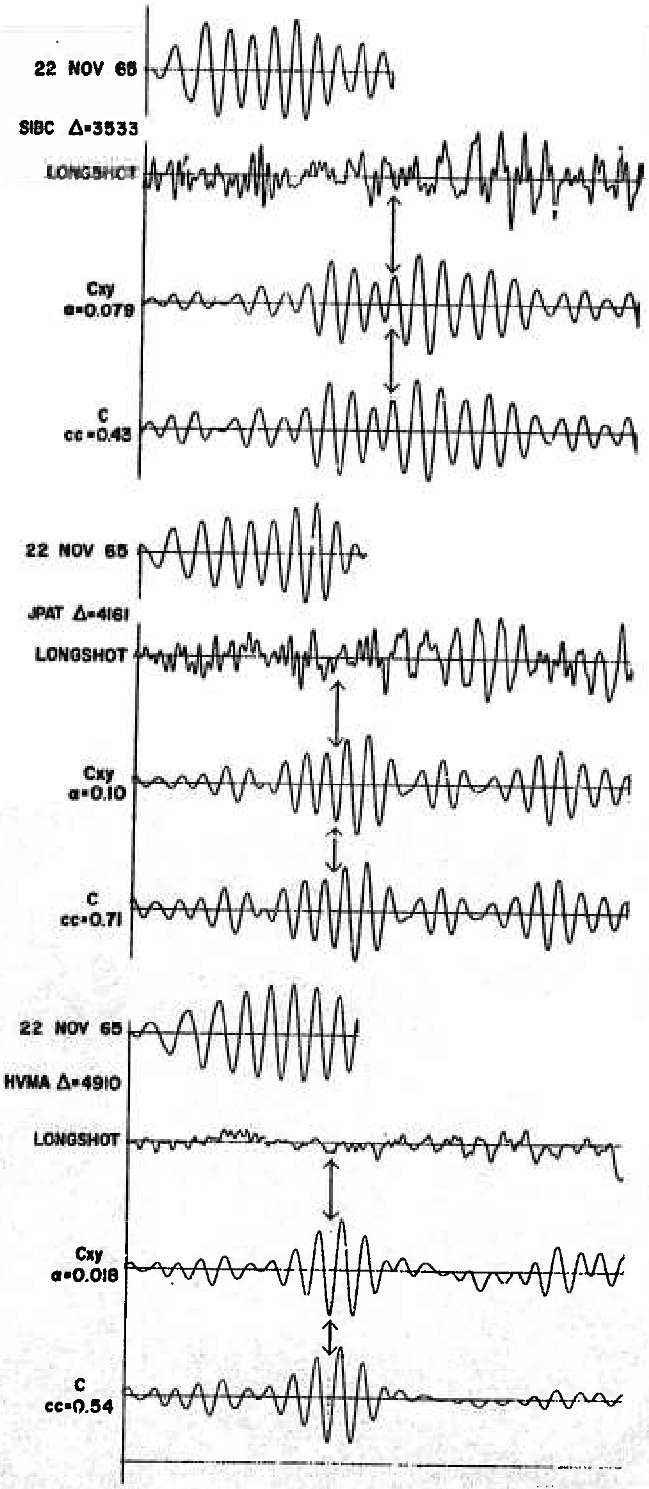

Figure 1. Matched Filter Analysis of LONGSHOT (m = 5.97) Rayleigh Waves with 22 November 1965 Earthquake (m = 5.9) Rayleigh Waves

the R/P excitation for an equivalent size earthquake.

Figure 2 shows the matched filter results for the magnitude 4.0 earthquake (20 February 1966) listed in Table I. Notice that the source depth for this event was 48 km which means that the surface wave excitation is necessarily smaller than if the same source were located closer to the surface. From Figure 2 it appears that this event was barely detected at several stations but not detected at every station. The values of $\hat{a}$ average about .01 which is approximately the value expected for a magnitude difference of 2. Certainly this event is at or near the lower limit of detectability using the matched filter approach.

2. Kamchatka Source Region

From Table I, it can be seen that in these cases the observing distances were in the range 5,300-8,000 km which overlaps, but extends further than the distances investigated for the Aleutian events. It can also be seen that all these events are located within 2-3 degrees of each other.

Results from the 5.3, 5.1, and 5.0 magnitude events clearly showed that the events were positively detected. Shown in Figure 3 are some of the matched filter results for the 21 January 1965 4.4 magnitude event. It should be noted that this was a deep focus event (119 km), hence equivalent to a smaller magnitude shallow event as far as Rayleigh wave excitation is concerned. It appears that this event was barely detected by the method with estimates of $\hat{a}$ around .03. This value gives a magnitude estimate of about 4.2 for the 21 January event, which seems large, considering the source depth of 119 km. In any case this event appears to define the threshold of detectability for the Kamchatka region.

3. Hawaiian Source Region

Results from both the 4.4 and 4.1 magnitude events shows that both were apparently detected. In figure 4 are shown the results for the shallow focus (11 km) magnitude 4.1 event of 13 August 1964. This event is apparently detected at most of the stations. However, the corresponding correlation coefficients and the estimates of $\hat{a}$ are small. The apparent magnitude of the small event is about 1.6 smaller than the reference event. However, the filtering effect of oceanic propagation of Rayleigh waves will greatly attenuate periods shorter than about 15 seconds and as the peak in excitation shifts to shorter periods for the smaller magnitude events, this effect should cause very significant reductions in surface wave energy, hence reduce the matched filter.

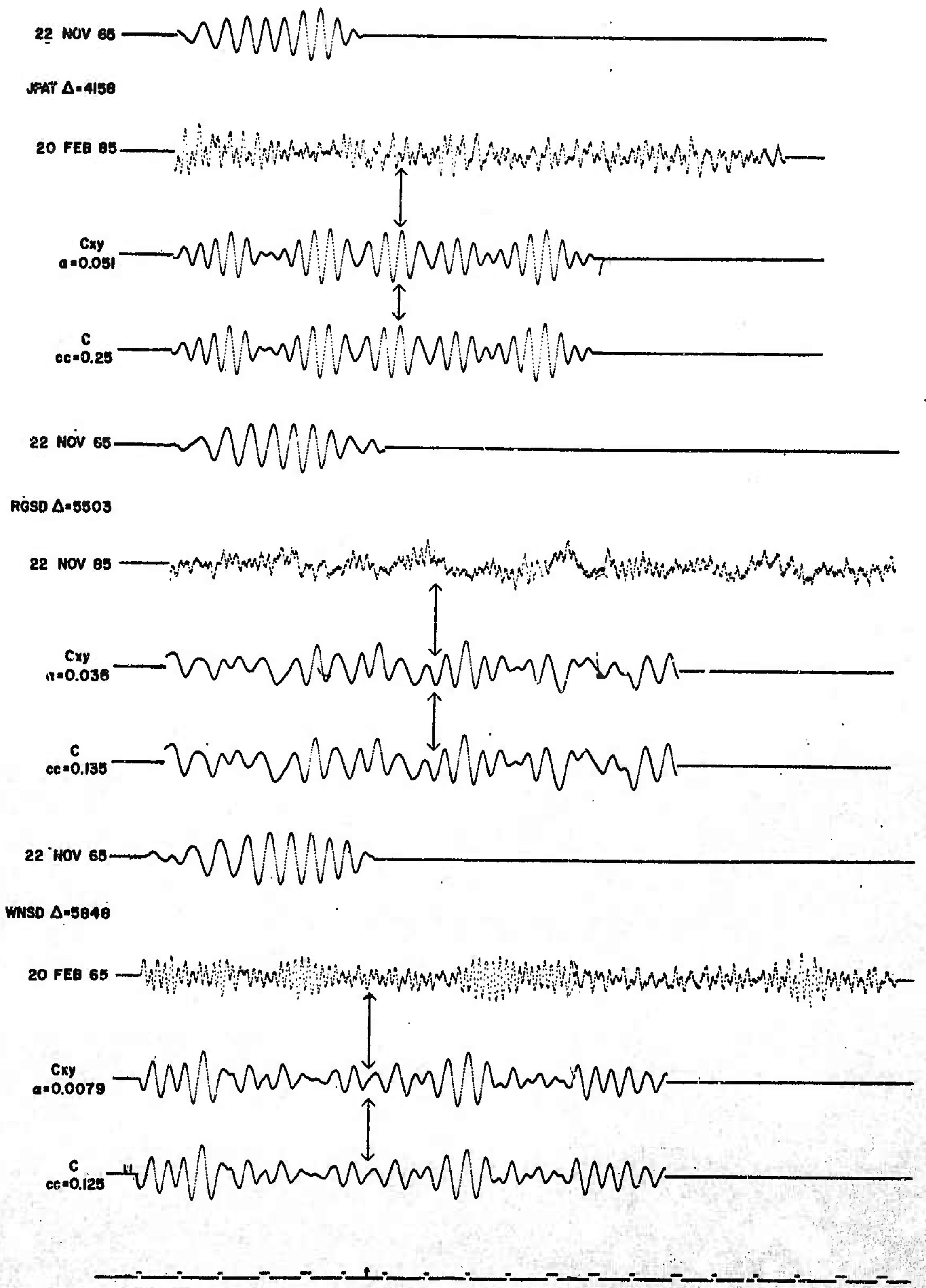

Figure 2. Search for Rayleigh Waves From a Magnitude 4.0 Event at Depth 48 km. Using 22 November 1965 Magnitude 5.9 Event.

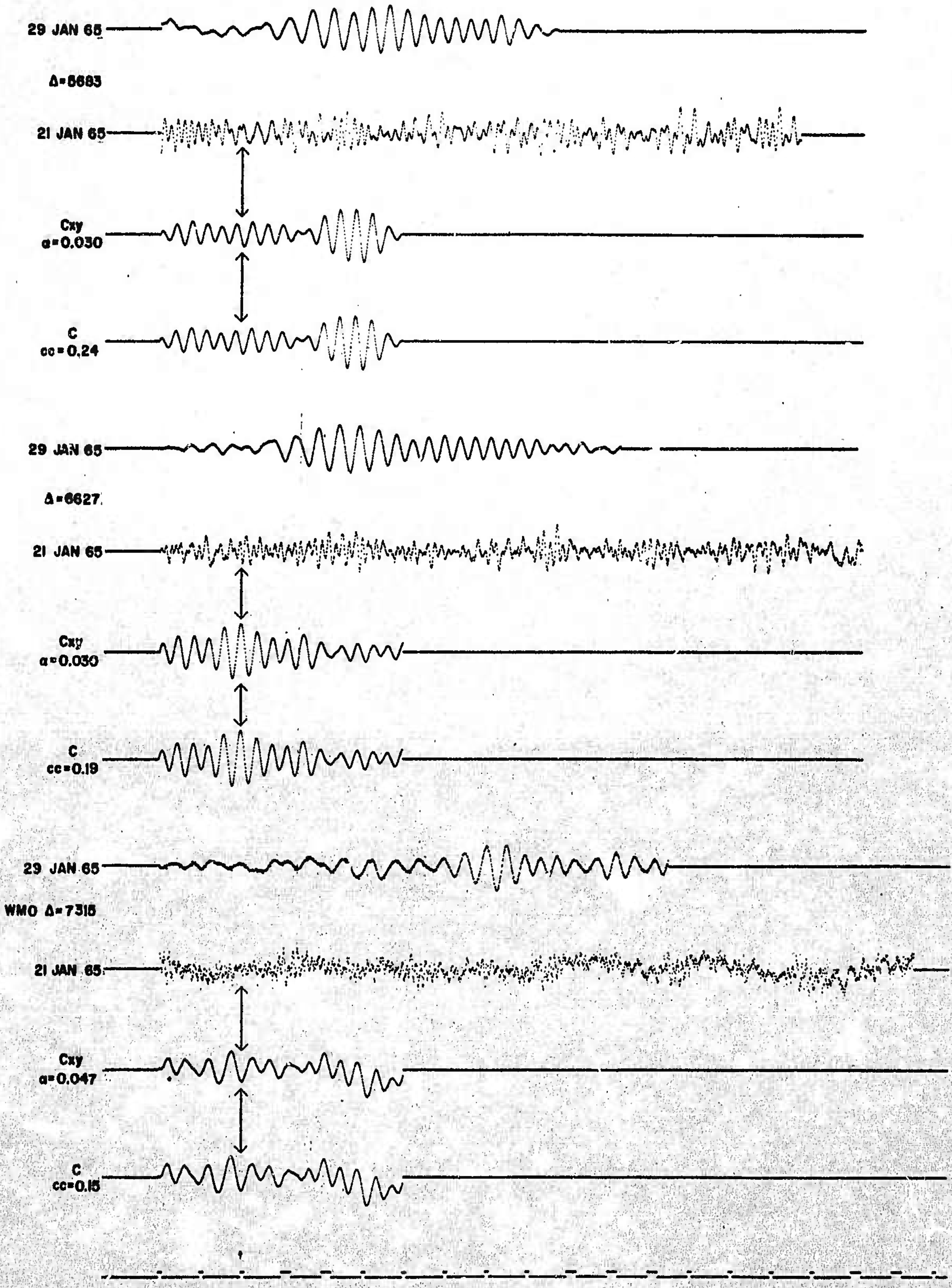

Figure 3. Search for Rayleigh Waves From a Magnitude 4.4 Event at Depth 119 km. Using the Magnitude 5.8 Event of 29 January 1965.

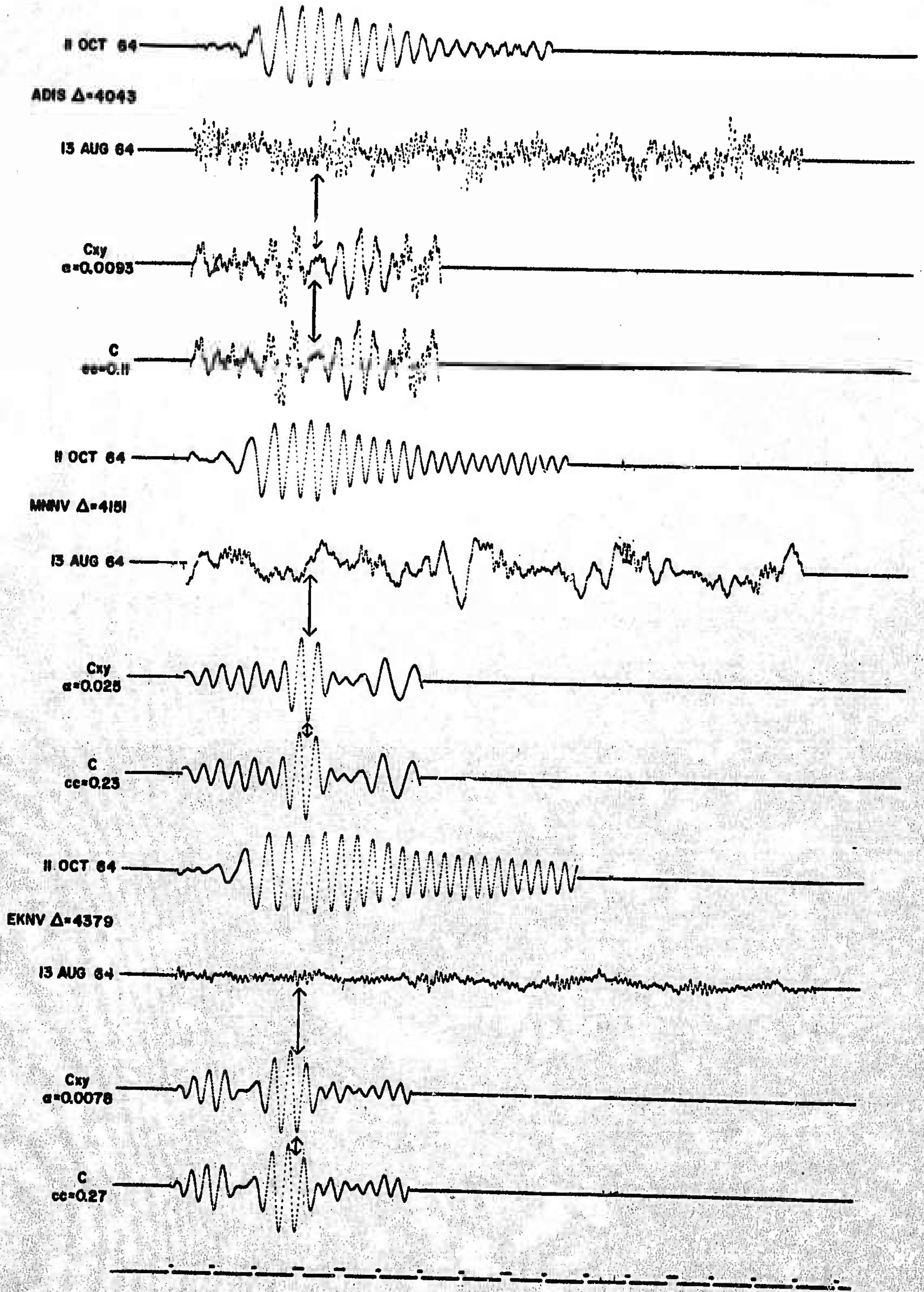

Figure 4. Search for Rayleigh Waves From a Magnitude 4.1 Event (13 August 1964) Using Those From a Magnitude 5.3 Event (11 October 1964) in Hawaii.

It has been demonstrated experimentally that the surface waves from small events can be detected at teleseismic distances using a matched filter method and that reasonable estimates of some source characteristics can be made. What has not been demonstrated is the minimum threshold of detection for the method. The underlying difficulty which always can affect the estimated threshold seriously is that the body wave magnitudes used as an obsolute standard for comparing events may be badly in error. A more reliable absolute measure of source strength is needed to evaluate the performance of the matched filter in detecting actual events.

One of the most useful features of the matched filter method is that it permits one to make meaningful surface wave magnitude estimates even when the signal to noise level is so low that one cannot visually detect the presence of the signal. This means that the matched filter method can be used to obtain reliable surface wave magnitude estimates for events so small that meaningful AR estimates of magnitude cannot be obtained.

It is concluded that:

1. In principle the matched filter approach can be used:
   (a) to detect weak surface wave signals for signal to noise ratios as low as about 0.35;
   (b) to make reliable relative magnitude estimates for S/N as low as .5;
   (c) to determine radiation pattern relative to a reference event;
   (d) to estimate the general shape of a small event's amplitude spectrum relative to that of the reference event.

2. The results presented for a number of actual events have demonstrated the practical applicability and usefulness of the matched filter approach in studying weak teleseismic surface waves.

3. The matched filter used in conjunction with the surface wave arrival time patterns appropriate for different source regions of interest allows one to discriminate against all but those events in the particular source region of interest.

4. Rayleigh waves produced by the LONGSHOT explosion were detected at teleseismic distances. The excitation of LONGSHOT Rayleigh waves, however, was an order of magnitude smaller than the Rayleigh wave excitation for an equivalent magnitude earthquake in the same region.

5. Love waves could not be detected for the LONGSHOT explosion.

6. Teleseismic surface wave signals could be detected for small earthquakes of body wave magnitude less than 5 in each of the three

different source regions investigated. The actual lower limit for each region is still uncertain.

B. The (pP-P) Time Difference

There is a difference in the travel-time anomaly for P and pP at the TFO Extended Array. This difference is sufficient in some cases to result in near cancellation of pP if the seismograms are summed by aligning on P. On most seismograms it is not possible to determine the time of pP with sufficient accuracy to justify the above statement. If, however, the examples are limited to seismograms with well-defined pP, then the scatter of the time difference (pP-P) can be demonstrated.

Four groups of seismograms were selected from the vertical seismograms recorded at the TFO Extended Array for the following earthquakes:

Chile-Bolivia Earthquake - 16 April 1965
Peru Earthquake - 10 May 1965
N. Coast Chile Earthquake - 20 July 1965
Kurile Is. Earthquake - 18 May 1965

The time difference (pP-P) observed at the 9 stations of the TFO Extended Array for the above earthquakes were plotted on Figure 5 against Δ (surface distance). In each case the scatter of the points was about 0.5 seconds. The points were read by timing a well-defined peak or through, rather than attempting to read first motion.

The parametric lines in Figure 5 were plotted from the Jeffreys-Shimshoni Tables (Jeffreys and Shimshoni 1964). They establish a norm against which the slope and scatter of the pP-P times may be measured. The parametric values of h/R for values other than 0.00, 0.01 and 0.02 were interpolated from the tables.

As a result of using well-defined phases and selected earthquakes the times for both P and pP are believed to be correct with 0.1 second.

The Jeffreys-Bullen tables predict an increase in the time difference (pP-P) as a function of Δ (surface distance) and depth of focus measured by h/R, where h is hypocentral depth minus 33 km. and R is the earth's radius. This increase is measured by the slope of the h/R plots of Figure 5. It varies from 0.1 second for the Kurile Earthquake to slightly more than 0.2 seconds for the Chile-Bolivia Earthquake across the range of surface distances measured by the TFO Extended Array. The spread of surface distances, observed by the TFO Array, is commonly 3^{o} to 4^{o}, varying with azimuth.

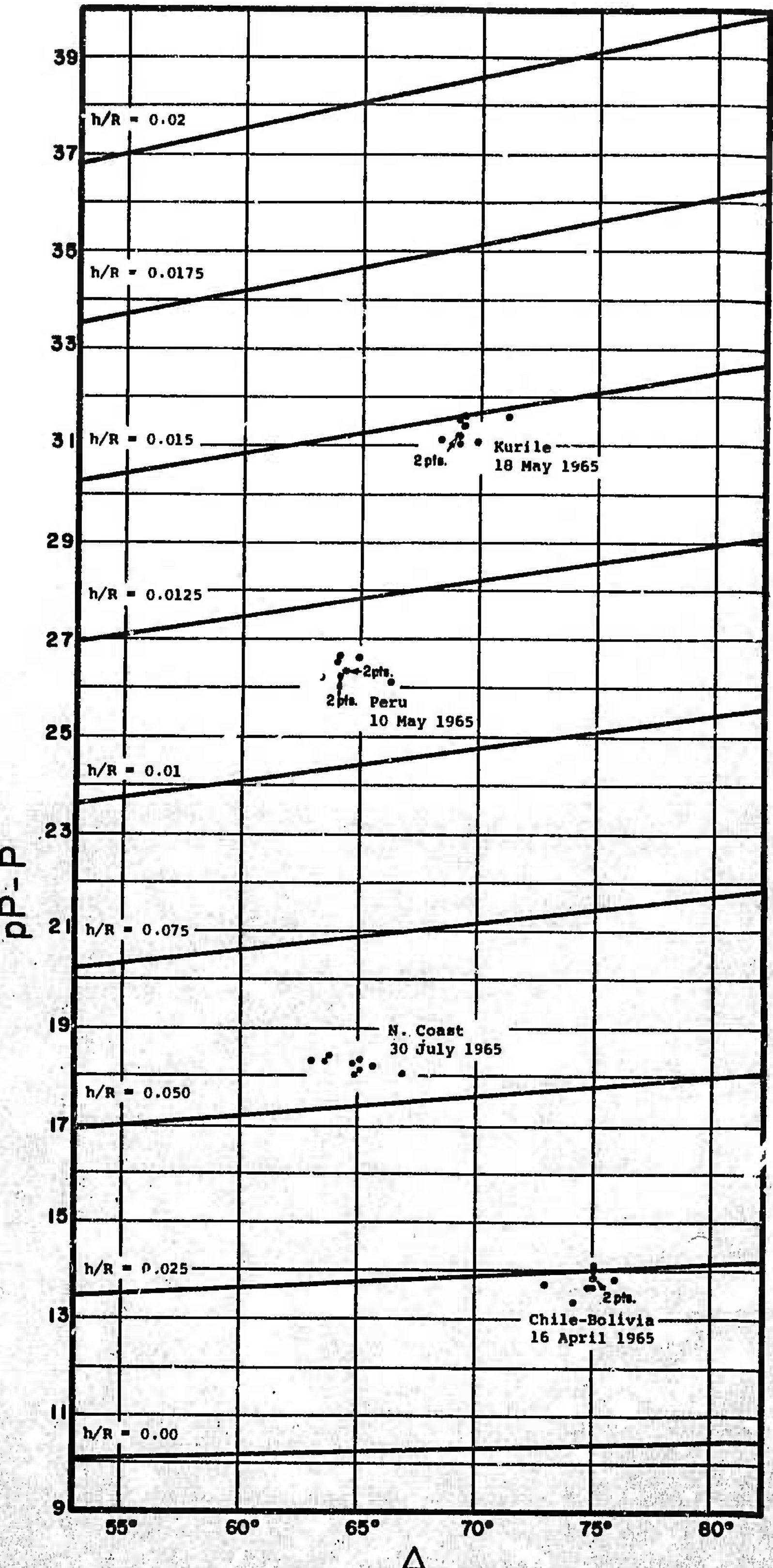

Figure 5. (pP-P) - Times

The visual evidence from the scatter of the plotted values of (pP-P) is clearly shown. In order to obtain a statistical measure of this scatter the following analysis was made. The relative smallness of the sample limits the conclusions to an indication of the confidence limits.

The mean and variances of the observed values of (pP-P) were computed using the standard formulas.

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i$$

and

$$s_{\chi}^{2} = \frac{1}{n-1} \sum_{i=1} (\chi_i - \bar{\chi})^2$$

The 95% confidence intervals of the variance were estimated from the following formula

$$\frac{(n-1)\ s_{\chi}^{2}}{\chi^{2}0.025} < \sigma^2 < \frac{(n-1)\ s_{\chi}^{2}}{\chi^{2}0.975}$$

If the observed times for (pP-P) are all 0.1 second greater or less than the mean, the time differences of a pair becomes 0.2 seconds. The phase difference of 1.0 sec period pulse is 1/5 x 360° or 72°. This would be sufficient phase difference to produce some distortion: however, the signal would probably be recognizable. If this assumption is used as a basis for computation then

$$0.0367 > \sigma^2 > 0.00457$$

This is the 95% confidence region, for the assumption each time is 0.1 sec greater or less than the mean is the above range. This difference (72° for 1 sec period) can be thought of as a threshold. If the time differences are greater, say 0.2, then the phase shift is 144° and summing produces near cancellation. This criteria of cancellation is not readily established, since the pulses to be summed contain a range of frequencies. It is probable that for reinforcement to occur, when the pulses are summed, requires a narrower range of variance than the range computed for the 0.1 second assumption. In each case the actual 95% confidence interval is greater than that computed for the 0.1 sec. assumption.

C. Design, Test, and Evaluation of Pre-set Bandpass Filters

The two filters selected for evaluation of performance were:

1. 2-Pole Phaseless High Pass Filter - this is set with the 3 db point at 1 cps and only suppresses the .2 cps peak in the noise. It gave no visible distortion of any of the signals, including first motion.

2. Second Order Gapped Finite Difference operator with the first spectral peak at 1.1 cps and the first null at 2.2 cps. It suppresses the .2 cps and the 2 cps noise peak and gave only slight distortion in the 1 cps signal but gave considerable distortion in the 1.8 cps signal.

Noise was obtained from a pseudo random number generating function, tested and shown statistically to provide a sequence of uncorrelated numbers. A synthetic signal was obtained by taking the displacement potential as an impulse into a system which models linear creep by a dashpot and spring, in series.

This noise and signal were used to evaluate these two filters. Results confirmed earlier findings from using real data. The gapped second difference filter appears to yield the best performance as a simple detector. The indicated gain in S/N ratio of 8.5 db and gain in threshold of 7.5 db are compared with the high pass filter's performance of 3.5 db and 2.5 db, respectively. One of the keys to optimum selection of bandpass filters appears to involve the suppression of spectral peaks occurring in the noise spectrum, especially the 0.2 cps and 2.0 cps peaks. How this is best done with minimum signal distortion is not resolved here: however, the gapped difference operator was the best design evaluated. Any distortion introduced by the filter can be effectively removed after array processing.

D. Noise Analysis of Single Channel Deghosting Filters

The purpose of applying a single channel inverse deghosting operator is to suppress the echo reflected at the earth's surface. For teleseismic signals, the incidence angle is approximately 15°, thus the down-going pulse could be modeled with a reflection coefficient of 0.9 and the up-going pulse with a reflection coefficient of 1.1. In practice, however, reflection coefficients greater than 1.0 lead to unstable operators, so that single channel echo-suppression is feasible only if it is attempted to partially remove the echo in isolating the up-going and down-going pulses.

Two different deghosting methods, two different bandpass filters and unfiltered data were the five cases evaluated by performance arrays. To produce each element in the array we operated on four minutes of data: each array, 16 hours of data, and for all five cases, 80 hours of data. The fact that all of these performances figures were computed with less than 40 minutes of computer time attests to speed of the bandpass and deghosting operators.

Results showed that arrays of performance values showing the change in noise variance due to deghosting indicate significant sensitivity to both the deghosting method and pre-band pass filtering. As a specification for single channel deghosting, the apparent reflection coefficient used to derive the operator, should be constrained such that the noise amplification does not exceed a specified design criteria such as 1 db. The apparent reflection coefficient used to design the echo suppressor is observed as highly dependent on the echo time.

III. SUPPORT AND SERVICE TASKS

A. VELA-UNIFORM Data Services

As part of the contract work-statement, the SDL provided one or more of the following support and service functions for VSC and other VELA participants:

- copies of 16 and 35 mm film
- playouts of earthquakes and special events
- copies of existing composite analog tapes
- composite analog tapes of special events
- use of 1604 computer for checking out new programs or running production programs
- copies of digital programs
- digitized data in standard formats or special formats for use on computers other than the 1604
- running SDL production programs, such as power spectral density and array processing on specified data
- digital x-y plots of power spectra or digitized data
- signal reproduction booklets
- copies of MIT Geophysics Program Set II
- space for visiting scientists utilizing SDL facilities to study data and exchange information with SDL personnel

During this report period, 52 such projects were completed and the 14 organizations receiving these services are listed in Appendix A.

B. Data Library

The Data Library contains digitized seismograms, digital computer programs and composite analog magnetic tapes, all available for use by the VELA-UNIFORM program.

The following additions were made during this period.

1. Digital Seismograms - 317 including
   - data from 32 explosions and 5 underwater events
   - noise samples from LASA, TFO, UBSO, CPSO, and WMSO
   - noise from several vertical arrays
   - earthquake data recorded at various stations from 15 events

2. LASA Data - 127 digital tapes
   - in addition to the LASA digital tapes in the library, there is also a master calibration tape which contains the magnification (digital counts per millimicron) of each sensor for every subarray. These magnifications have been computed for all calibration tapes currently in house. As each new calibration is received, it is routinely run through the program CALIBR and added to the master tape.

3. Digital Programs - 11 including:

<u>APCTTAT</u> -
To take an input tape containing a label and (NC) no. of data channels, obtain all possible combinations of NC taken two at a time, and form an output tape containing a label with each set of two records.

<u>COHERENCY</u> -
To compute all the ordinary coherencies, auto-spectra, and phase relations of a set of input data channels.

<u>FKSPTRUM</u> -
To compute and display the frequency-wave number power spectra of seismic noise along with a response function for the corresponding array. This program is intended as a replacement for certain parts of program, PEAKAY using the Cooley-Tukey method to estimate auto and cross power spectral density functions.

<u>FSTMOFIL</u> -
To perform recurrsive filtering of seismic data using two methods, namely RECFIL and SDL, in order to determine the one which preserves first motion best.

MAKESUB -

To read an input seismogram and produce another seismogram containing the altered label and data. The channels of data may be detrended, scaled, segmented, or completely omitted. The label is changed accordingly.

MAXLIKE-21 -

This Fortran-63 program computes and applies a 21 point maximum-likelihood digital filter (realizeable or symmetric) to seismic array data.

RODRDATA -

To take an input tape containing a set or sets of logical records (a label and so many data traces constitute a set) and generate a new tape with any or all of the data records within any set re-written such as to change their order of occurrence.

SIMVARRY -

To simulate an N component vertical array according to the different criteria.

TWX -

To compute a least-mean-square-error filter which interpolates one channel of an array from certain other channels in the array, apply the filter to construct an interpolated estimate, construct the error time function, and display the power spectrum of the error.

VERPROC -

To process vertical array data in the following different ways.

XMNG -

This is a package of three Fortran-63 subroutines for computing an estimate of the spectral matrix for N channels of taped data.

4. Analog Composite Tapes - 10 including:

(a) Made by SDL

- GREELEY
- STERLING
- CHASE V
- PRESTERLING
- One event for Geotech, Teledyne, Inc.
- Three events for Texas Instruments, Inc.

(b) Made by Geotech

- PIRANHA
- CHASE VII

C. Data Compression

This is a continuing routine operation, and production is maintained at the level needed to meet the requirements of the field operation (LRSM and U. S. Observatories) and the Seismic Data Laboratory. For this period, 3,795 tapes were compressed.

D. Automated Bulletin Process

September, October, November, and December 1966 LRSM and Observatory bulletins were processed during this report period and forwarded to Geotech, Teledyne, for checking and publication.

APPENDIX A

ORGANIZATIONS RECEIVING SDL DATA SERVICES

JANUARY - MARCH 1967

Dominion Observatory

Earth Sciences, Teledyne

General Atronics Corporation

Geotech, Teledyne

Oregon State University

Pennsylvania State University

Princeton University

RADC

Southern Methodist University

St. Louis University

Texas Instruments, Inc.

Underwater Systems, Inc.

U. S. Coast and Geodetic Survey

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11. SUPPLEMENTARY NOTES ---	12. SPONSORING MILITARY ACTIVITY ADVANCED RESEARCH PROJECTS AGENCY NUCLEAR TEST DETECTION OFFICE WASHINGTON, D. C.

13. ABSTRACT

This report ~~discusses~~ the work performed by SDL for the period January through March 1967, and ~~is~~ primarily concerned with seismic research activities leading to the detection and identification of nuclear explosions as distinguished from earthquake phenomenon. Also discussed are the data services performed for other participants in the VELA-UNIFORM project.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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VELA-UNIFORM Project						
Seismic Data Analysis						
Surface Waves						
TFO Extended Array						
Bandpass Filters						

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